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Fuel cell cogeneration system: a case of technoeconomic analysis

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Abstract

Fuel Cell is the emerging technology of cogeneration, and has been applied successfully in Japan, U.S.A. and some OECD countries. This system produces electric power by an electrolytic process, in which chemical substances (the most utilized substances are solid oxide, phosphoric acid and molten carbonate) absorb the components H_2 and O_2 of the combustion fuel. This technology allows the recovery of residual heat, available from 200°C up to 1000°C (depending on the electrochemical substance utilized), which can be used for the production of steam, hot or cold water, or hot or cold air, depending on the recuperation equipment used. This article presents some configurations of fuel cell cogeneration cycles and a study of the technical and economic feasibility for the installation of the cogeneration systems utilizing fuel cell, connected to an absorption refrigeration system for a building of the tertiary sector, subject to conditions in Brazil.

1. Introduction

Cogeneration may be defined as the simultaneous production of electric power, and useful heat, from the burning of a single fuel. This technique of combined heat and power production has been applied successfully in industrial and tertiary sectors. It occurs mainly because of efficient technology levels, and also the guarantee of the available electricity and low level environmental impacts.

The cogeneration systems utilizing internal combustion engines (Otto and Diesel versions), steam turbines and gas turbines in open cycle, are the most utilized technologies worldwide. However some emerging technologies have become actual applications, [1] e.g.:

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- Gas turbine in closed cycles;
- Fuel Cell Systems (FCS).

The FCS has been developed with efficiency levels up to 90% of the fuel power, and presents a lower emission level of pollutants in comparison with other technologies. The FCS can be applied from 10 kW up to 50 MW [2, 3].

This article presents, firstly, some technical information about the most difunding types of the fuel cell demonstration systems in the world, and secondly, the energetic and economic analysis of a molten carbonate fuel cell in the cogeneration version as applied in the computer center building. The system produces electrical power and cold water for the building. The residual heat of the FCS is utilized as the power source of an absorption refrigeration system responsible for the air conditioning.

2. Fuel cell system (FCS)

The basic concept of FCS is not complex. The operation principle is an electrochemical reaction which produces electrical power at low voltage (in direct current). Through an external circuit, FCS converts the chemical substances H_2 and O_2, of the fuel and air, in electricity and water, as a byproduct. This process may be understood as the inversion of the electrolyze of water, and it is known as the electrolytic process.

In an FCS, the H_2 extracted from the fuel, in a process called reforming, is introduced to an anode (negative) electrode. An oxidant (O_2) is introduced to the cathode (positive) electrode. As a result of the electrochemical process that takes place on each side, ions flow across the cell and electrons flow through the external circuit producing electricity. Carbon dioxide, water and heat are also produced by this process. Figure 1 shows a typical FCS, according to Siemens [4].

An individual cell has a fairly low output so cells are stacked to achieve the desired voltage. The heart of the process is the electrolyte, which can be made of a variety of substances such as alkalines, solids, or salts. The various electrolytes identify the types of fuel cells. The FCS power plants are configured in three major sections, (a) a fuel processing or reforming section, (b) the fuel cell stacks, and (c) a power conditioning section.

The reforming section's primary function is to convert a hydrocarbon-rich fuel into hydrogen and the steam reforming of the fuel can be used for this purpose. The fuel processor must clean the fuel and remove compounds, such as sulfur, that can poison the catalysts in the reformer and cells.

The plant section encompassing the fuel cells provides the equipment to feed or exhaust reactants from the cells, maintain cell stack conditions, manage the heat rejected by the stack and the electric circuit. In the power conditioning section the direct current is converted to alternate current at proper voltage levels before it is sent to the grid.

The FCS approaching commercial availability for cogeneration system application are of three types: (1) Phosphoric Acid Fuel Cell (PAFC), (2) Molten Carbonate Fuel Cell (MCFC) and (3) Solid Oxide Fuel Cell (SOFC) [5].

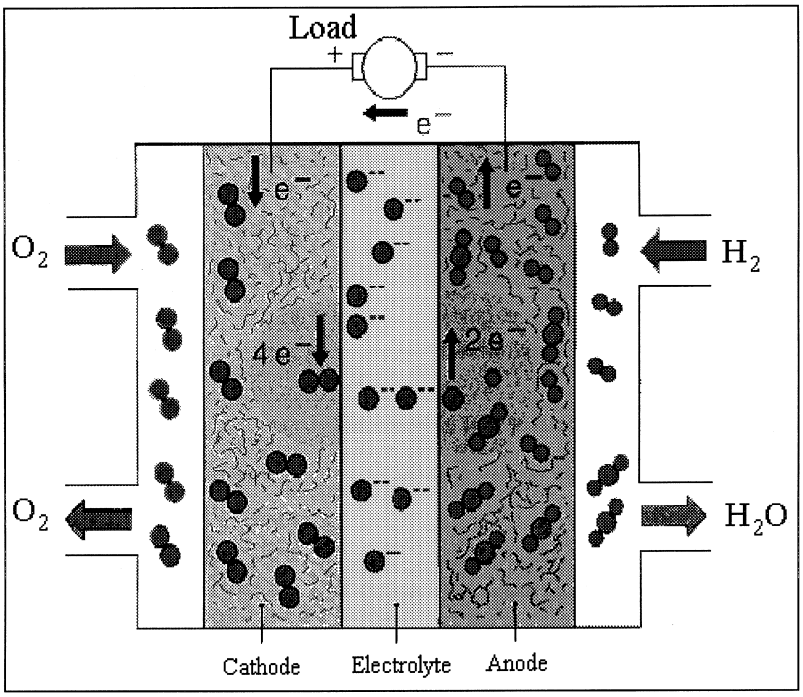

Fig. 1. Basic fuel cell system [4].

The first type (PAFC) is the most difunded and the nearest to commercialization. This type of FCS gives a low operation temperature (about 200°C), and an electrical efficiency of about 43%. The commercial development of the PAFC system has already begun in the U.S.A., in some countries of the European Community, and has been mostly funded in Japan where the biggest FCS power plant of this version is located in Goi City, and with 11 MW of electrical power is under the responsibility of the Tokyo Electric Power Company [5].

The MCFC presents higher levels of electrical efficiency, about 48–55%, and is supposed to out do the PAFC, mainly because of the level of operation temperature (about 650°C). On the other hand, the SOFC is not so distant from the development course, giving higher operation temperatures (about 1000°C) and a similar level of electrical efficiency to that of the MCFC [5, 6].

The main advantage of the FCS when compared with the use of steam turbine or gas turbine power plants is related to NOx emission (Fig. 2) [6].

3. Some configurations of fuel cell cogeneration cycles

The first field of application for heat and power fuel cells will be the decentralized power supply in the 1 MW range. The SOFC-based power and heat supply for an office block is shown in Fig. 3 [4].

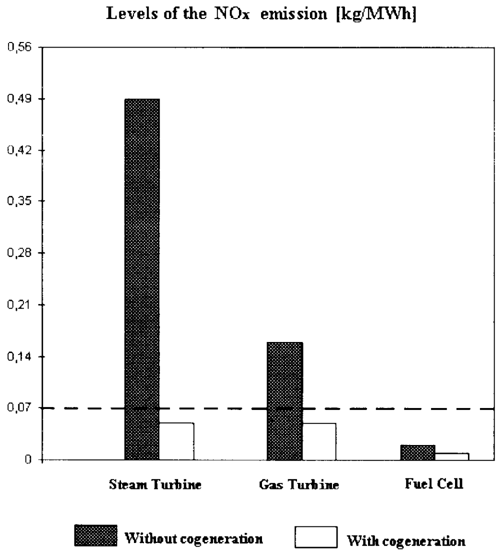

Fig. 2. Levels of the NOx emission.

Larger units, e.g. for 40 MW, can also be used to generate power on the central station scale (Fig. 4). In this case a gas and steam turbine combined cycle is added so that an electrical efficiency of about 68% is obtained for a plant powered by an internally reformed natural-gas-fueled solid fuel cell [4].

The unit is also suitable for supplying process steam in industrial applications. In

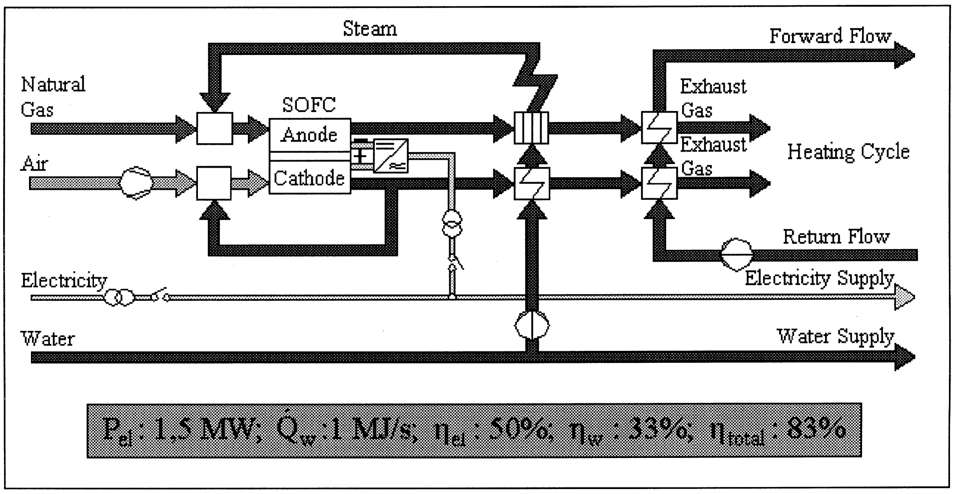

Fig. 3. High temperature fuel cell (SOFC) for electricity and heat supply to an administration building [4].

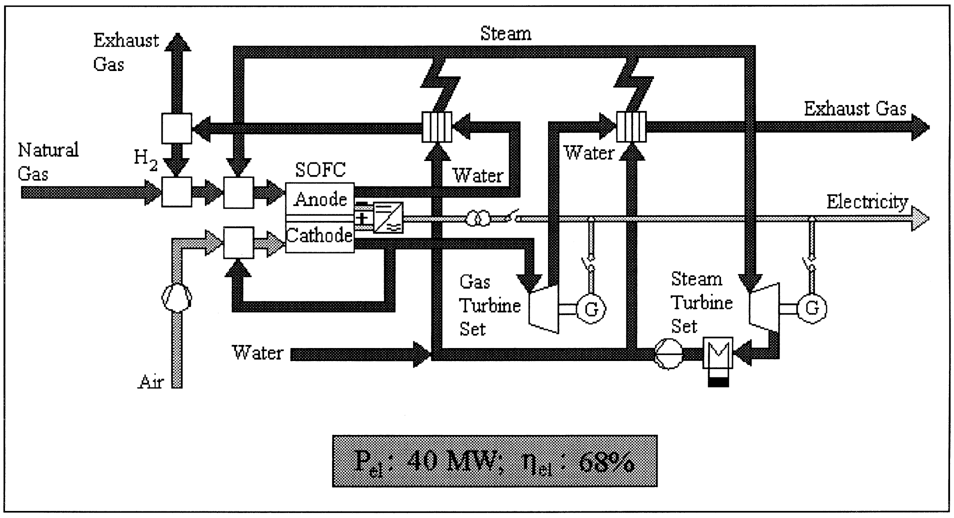

Fig. 4. High temperature fuel cell power station for industrial applications (maximum electricity generation) [4].

this case the electrical efficiency is reduced to 65%, and about 10% of the output can be used for heat supply (Fig. 5) [4].

4. Technoeconomic analysis of a fuel cell system

In this case we have analysed an FCS to produce electricity and cold water at 7°C for the air conditioning system, in a computer center building.

For this purpose an MCFC associated with an absorption refrigeration system was chosen, in order to meet cold water production (cogeneration system in thermic parity operation). In this case the exhaust gases of the FCS are used to run the absorption refrigeration system aiming at sufficient cold water production necessary for the building. Figure 6 shows the cogeneration system proposed.

The main parameters of system components are presented based on some existing situations [2, 5, 6]. When necessary, supplementary information was introduced for the calculus procedures.

The mass and energy balances are essential tools for the intended analysis in this study. Allowing for the materials input and output flows which were not measured, the mass balance must aid energy balance. This in turn, permits the evaluation of the energy inputs and outputs in the components of the system, facilitating the operational alternatives and design.

Table 1 shows the mass flux (m), temperature (T) and enthalpy (h) for the points indicated in Fig. 6.

The following considerations were made for the energetic analysis presented:

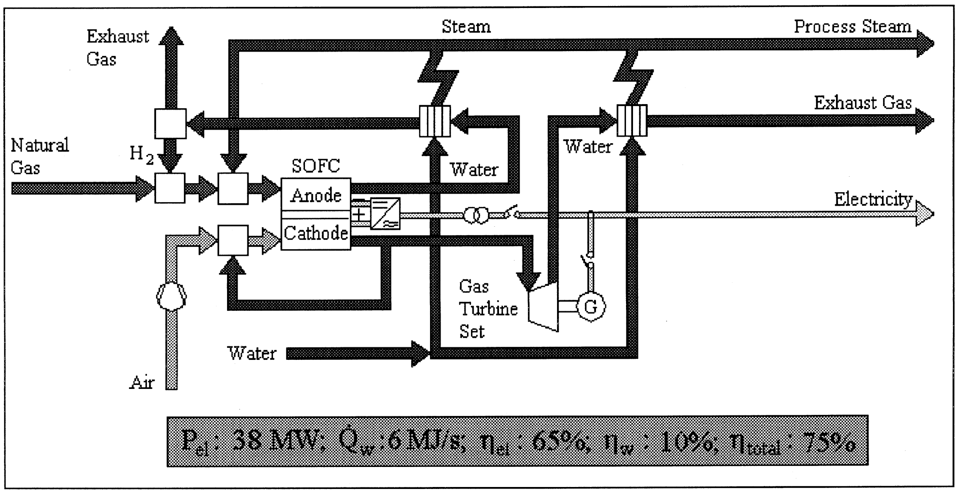

Fig. 5. High temperature fuel cell power station for industrial applications (maximum process steam extraction) [4].

- A value of 0.64 kg/m^3 for the gas natural density.
- A value of 0.65 for the performance coefficient of the absorption refrigeration system [7].
- A value of 51.5% for the thermal efficiency of the MCFC [8].

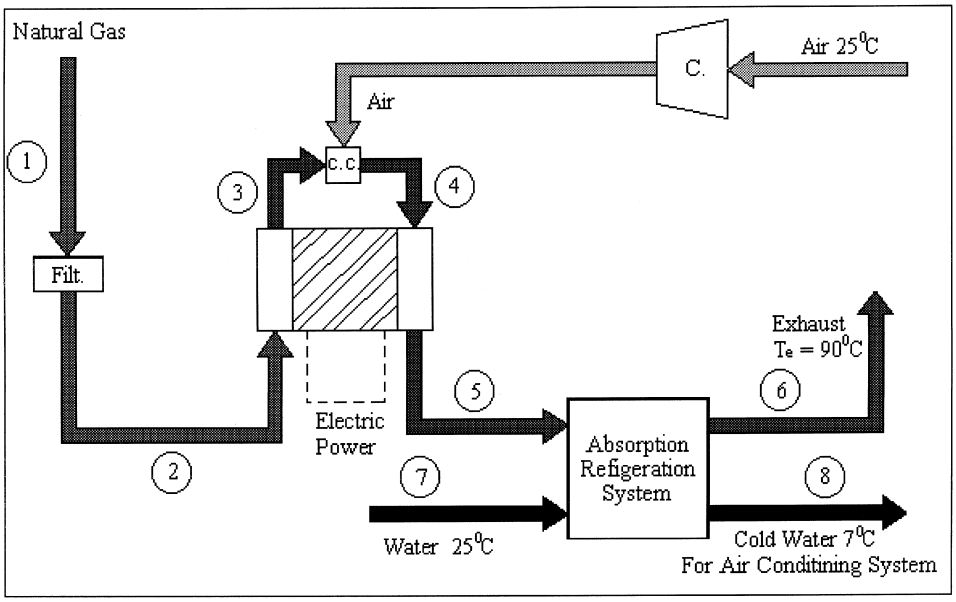

Fig. 6. Cogeneration system.

Table 1
Data for the points in Fig. 6

Points	m [kg/s]	T [°C]	h[kJ/kg]
1	0.005	25	298.31
2	0.005	25	298.31
3	0.005	250	526.90
4	0.198	1200	1603.31
5	0.198	650	958.80
6	0.198	90	363.69
7	1.008	25	105.00
8	1.008	7	29.43

Note: mair = 0.193 kg/s

- A value of 1.30 for the electricity/heat quotient [9].
- A value of 37,683 kJ/Nm^3 for the Lower Heat Value of the natural gas [10].
- A value of 90°C for the escape (to atmospheric) gases temperature according to the pinch-point procedures [1]. This latter value satisfies the necessary operation temperatures in the generator of the absorption refrigeration machines (LiBr and Water), which range from 60–90°C [7].

The performance parameters of the cogeneration system proposed are shown in Table 2.

The annual saving for the proposed system depends on the electricity and cold water production costs being competitive with conventional systems. The international experience shows that high electricity tariffs encourage investment in the cogeneration system with a capacity as shown in this study [11].

Considering a value of 0.011 US$/kWh [8] for the cost of natural gas; a value of 0.090 US$/kWh [11] for the electricity tariff and 6000 h/year for the equivalent utilization period, and still:

- According to Matsumoto [8] and Kuehn [5], the investment on FCS will be considered around 1000 US$/kW, for high production volume;
- On the other hand Krumpelt [12] has made a provision of the investment cost in FCS around 1500 US$/kW, also, for high production volume.

Table 2
Energetic performance

Electric power [kW]	152
Recovered thermal power [kW]	117
Fuel thermal power supply [kW]	295

Table 3
Electricity and cold water production costs in cogeneration

Annual interest rate %	For a value of 1000 US$/kW of investment cost in FCS		For a value of 4000 US$/kW of investment cost in FCS	
	Cel	Cag	Cel	Cag
8	0.0666	0.0341	0.1729	0.0341
12	0.0699	0.0348	0.1859	0.0348
16	0.0749	0.0358	0.2054	0.0358
20	0.0799	0.0368	0.2249	0.0368

Note: Cel = Electricity production cost in US$/kWh; Cag = Cold water production cost in US$/kWh.

Table 3 shows the electricity and cold water production costs considering the investment cost in FCS from 1000–4000 US$/kW [6] (for 100,000 and 1000 units produced, respectively) and considering a value of 200 US$/kW for the investment in absorption refrigeration system [11], taking into consideration a 6-year payback period.

It can be observed that the cold water production cost is the same for any investment cost value on FCS.

For an actual analysis, Fig. 7 shows the annual saving expected (R) as a function of the payback period (K), considering an annual interest rate of 8% and an investment cost on FCS raging from 1000–3000 US$/kW, depending on FCS production volume.

It may be observed that there is economic feasibility for the proposed cogeneration system for FCS investments values 1000, 1500 and 2000 US$/kW indicated 3.4, 5.8 and 7.6 years for payback periods, respectively.

5. Conclusions

The FCS has been developed and applied in a cogeneration version. There are demonstration units in the U.S.A., Japan and some countries of the European Community. This cogeneration technology has high efficiency and presents low levels of pollutants emission and may present power capacities from 10 kW up to 50 MW.

The investment values are estimated depending on the production volume. Some manufacturers such as Siemens, Westinghouse, Fuji, Mitsubishi, Toshiba and ONSI [5], have been producing units of FCS, which have been implanted as demonstration level. It tends to take to an actual commercialization and development of the FCS in cogeneration version.

Finally, for the proposed analysis in this article, the results show that there is technical and economic feasibility for FCS investment values between 1000 and 1500

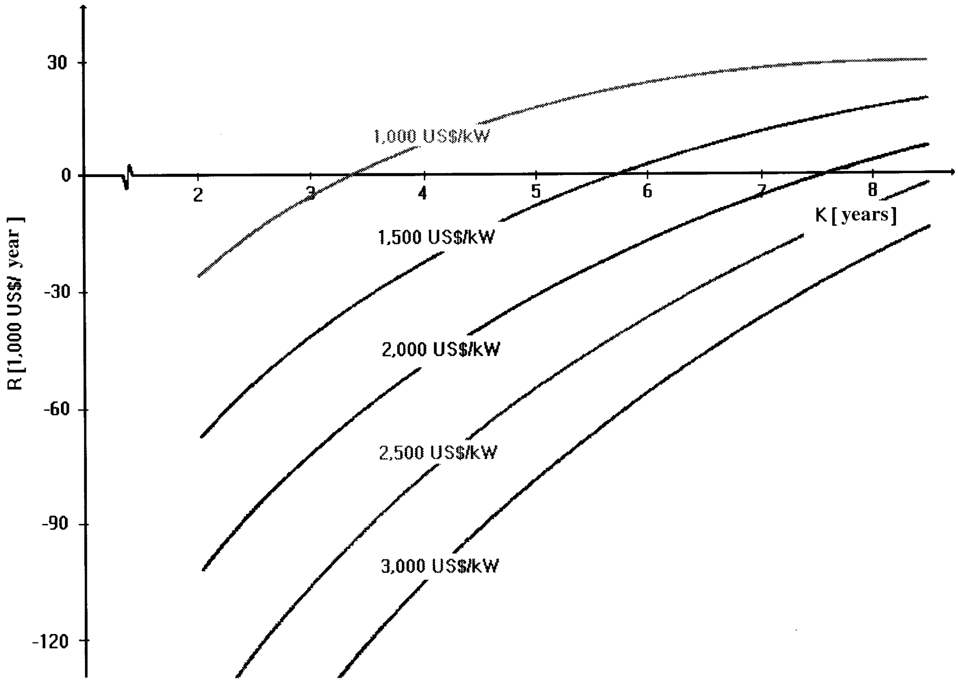

Fig. 7. Total annual saving as a function of the payback period.

US$/kW (for payback values between 3 and 6 years). These levels of investment are not distant for the coming years.

For a future article, we have been developing more detailed studies about the FCS in its various forms and applications.

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